

Aircraft Flap Control System: Proposal of a Simulink Test Bench for Evaluating Innovative Asymmetry Monitoring and Control Techniques

Original

Aircraft Flap Control System: Proposal of a Simulink Test Bench for Evaluating Innovative Asymmetry Monitoring and Control Techniques / Belmonte, Dario; DALLA VEDOVA, MATTEO DAVIDE LORENZO; Maggiore, Paolo. - In: INTERNATIONAL JOURNAL OF MATHEMATICAL MODELS AND METHODS IN APPLIED SCIENCES. - ISSN 1998-0140. - ELETTRONICO. - 10:(2016), pp. 51-61.

Availability:

This version is available at: 11583/2642537 since: 2016-05-18T02:13:41Z

Publisher:

NORTH ATLANTIC UNIVERSITY UNION (NAUN)

Published

DOI:

Terms of use:

openAccess

This article is made available under terms and conditions as specified in the corresponding bibliographic description in the repository

Publisher copyright

(Article begins on next page)

Aircraft Flap Control System: Proposal of a Simulink Test Bench for Evaluating Innovative Asymmetry Monitoring and Control Techniques

Dario Belmonte, Matteo D. L. Dalla Vedova and Paolo Maggiore

Abstract— One of the most important requirements in the design of secondary flight control actuation system is the proper limitation of the asymmetry between left and right wing flap surfaces; these asymmetries, that are typically due to mechanical transmission failures, must be timely detected and neutralized in order to guarantee the aircraft safety (especially during takeoff and landing flight phase in which the effects of these asymmetries could generate uncontrollable aircraft attitudes). In particular, when the angular asymmetry exceeds a defined critical value, the flap control system must detect and identify the incoming failure and actuate proper stopping procedures in order to limit this increasing asymmetry; to this purpose, it is necessary to conceive effective control algorithms able to perform an early fault detection avoiding false alarms.

In recent applications, the most commonly used architectures employ the reversible actuators with wingtip brakes and centrally located PDU (of a dual motor type for operational reliability) because it is cheaper and more efficient, nevertheless, especially in severe fault conditions (torque shaft break under very high aerodynamic load) could generate unacceptable asymmetries. Therefore the development of enhanced flap actuation systems based on innovative layout or enhanced monitoring and control techniques can improve significantly the operating performances of the secondary flight control systems.

In order to evaluate the behaviors of a real flap actuation system, simulating with a proper accuracy its dynamic responses and testing the performances of different monitoring and control algorithms, the authors propose a robust simulation developed in Matlab-Simulink numerical environment. By means the proposed numerical simulation model it is also possible to simulate a wide range of operating conditions (variable aerodynamic load, different mechanical layouts and several hydraulic and mechanical failures), to test new flap control system solutions (alternative architectures, new no-back devices or damping systems) and to evaluate the robustness of the aforesaid asymmetry monitoring techniques.

Keywords—Aircraft Secondary Flight Controls, Flap Actuation System, Control and Monitoring Algorithms, Flap Asymmetry, Mechanical Transmission Failures.

P. Maggiore is with the Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso Duca degli Abruzzi, 24 - 10129 - Torino, ITALY. (e-mail: paolo.maggiore@polito.it).

D. Belmonte is with the Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso Duca degli Abruzzi, 24 - 10129 - Torino, ITALY. (e-mail: Dario.belmonte@polito.it).

M. D. L. Dalla Vedova is with the Department of Mechanical and Aerospace Engineering (DIMEAS), Politecnico di Torino, Corso Duca degli Abruzzi, 24 - 10129 - Torino, ITALY. (corresponding author phone: +390110906850; e-mail: matteo.dallavedova@polito.it).

I. INTRODUCTION

THE flap actuation systems of most commercial and military aircraft consist of a centrally located Power Drive Unit (PDU), a shaft system and a certain number of actuators (normally two for each flap surface).

Secondary flight controls are a critical feature of the aircraft system as they actuate flap and slat surfaces fulfilling these main specifications:

- 1) on-off command type (discrete actuation mode)¹;
- 2) modification of wing aerodynamic coefficients;
- 3) actuation during take-off and landing phases, keeping the surfaces on a stable extracted position.

Depending on the performance requirements and on the specified interface with the other aircraft systems and structure, several different configurations have been used in the design of such actuation systems. PDU's can be either hydromechanical or electromechanical and be either of a single or dual motor type. In the last case the outputs of the two motors can be either torque summed or speed summed.

The shaft system generally consists of torque tubes connecting the PDU output with the right and the left wing actuators; however, the flap actuation systems of small commercial aircrafts often use flexible drive shafts rotating at high speed in place of the low speed rigid shafts.

The final actuators are often linear-type and are usually based on reversible screw actuators (i.e. ballscrew or rollerscrew devices specifically developed for such applications in the aeronautical field) though some solutions still use less efficient components like the acme and lead screws (usually irreversible or partially reversible); nevertheless, some solutions are also based upon rotary type systems (usually reversible).

These systems must be able to prevent asymmetries between the left and right wing flaps in case of a shaft failure (detected by a dedicated asymmetry monitoring system) and to hold the surfaces in the commanded position following the shutoff command given when no actuation is required.

¹The discrete flap/slat actuation is typical of civil and military transport aircrafts, but, especially for modern fighter aircrafts, have been developed most performant actuation systems, usually known as Combat Flap/Slat, characterized by a continuous actuation.

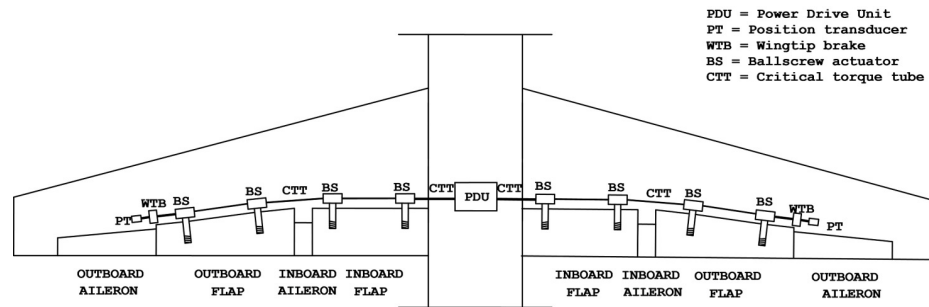


Fig. 1 Wing tip Brakes (WTB) Flap Architecture.

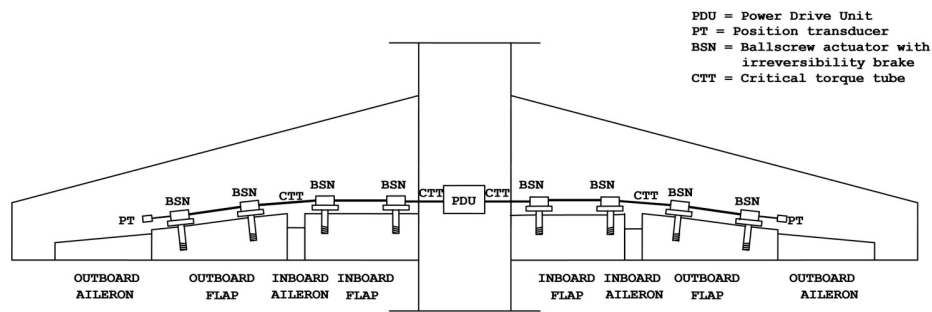


Fig. 2: No-Back Irreversibility Brakes (NBB) Flap Architecture

If the actuators use an irreversible screw, the above mentioned requirements are intrinsically accomplished; if the actuators are reversible (in order to obtain higher efficiency) a brake system is necessary:

- controlled wingtip brakes (one for each wing) located at the end of the transmission line, close to the position transducers (Fig. 1), that are engaged in order to brake the system after that a failure has been positively recognized;
- self-acting irreversibility brakes within each actuator, which self-engage when the actuator output overruns the input shaft (Fig. 2).

It must be noted that, in actual applications, the most commonly used architectures employ the reversible actuators with wingtip brakes and centrally located PDU (a dual motor type for operational reliability) because it is cheaper and more efficient, nevertheless the associated high asymmetries in case of failure. Whichever the actual configuration of the flap actuation system is, its dynamic behavior is strongly dependent from the actuator dynamics; so an appropriate actuator simulation model is necessary to evaluate the system behavior with a high degree of accuracy, both in failure and in normal operating conditions. A high compactness is recommended, nevertheless the high computational accuracy requested.

II. AIMS OF WORK

The aim of this work is to propose a numerical algorithm able to simulate the dynamic behavior of a typical flap actuation system, with a suitable level of accuracy, considering the effects due to the fracture shaft failure and non-linear physical phenomena. The proposed model (representing the whole electro-hydro-mechanical actuation system and the related asymmetry monitoring systems) has been validated comparing its behaviors with the results reported in [1].

III. SECONDARY FLIGHT CONTROL SYSTEM

As previously reported, the secondary flight control system, typically realized by means of electro-hydro-mechanic position SMs, modifies the aerodynamic characteristics of the aircraft wing adapting lift, drag and camber line profile to a defined flight condition (e.g. takeoff, landing or maneuvered flight).

In other words, flaps and slats are devices mounted on the trailing edges of the wings of a fixed-wing aircraft and typically used to alter the lift characteristics of a wing, reducing the speed at which the aircraft can be safely flown and increasing the angle of descent for landing. They shorten takeoff and landing distances lowering the stall speed and increasing the drag. There are many different types of flaps used, depending on the size, speed and complexity of the aircraft on which they are to be used, as well as the era in which the aircraft was designed. Plain flaps, slotted flaps, and Fowler flaps are the most common. Krueger flaps are positioned on the leading edge of the wings and are often used on many jet airliners. In this paper, as shown in Figure 3, the authors consider a Fowler flap configuration (i.e. a flap layout commonly used in aircraft and able to give a maximum lift coefficient increase up to 30% and the best profile camber).

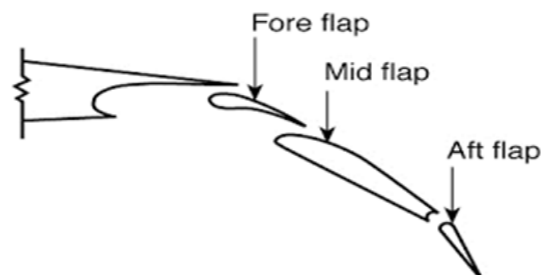


Fig. 3 Schematic Diagram for Triple Slotted Flap

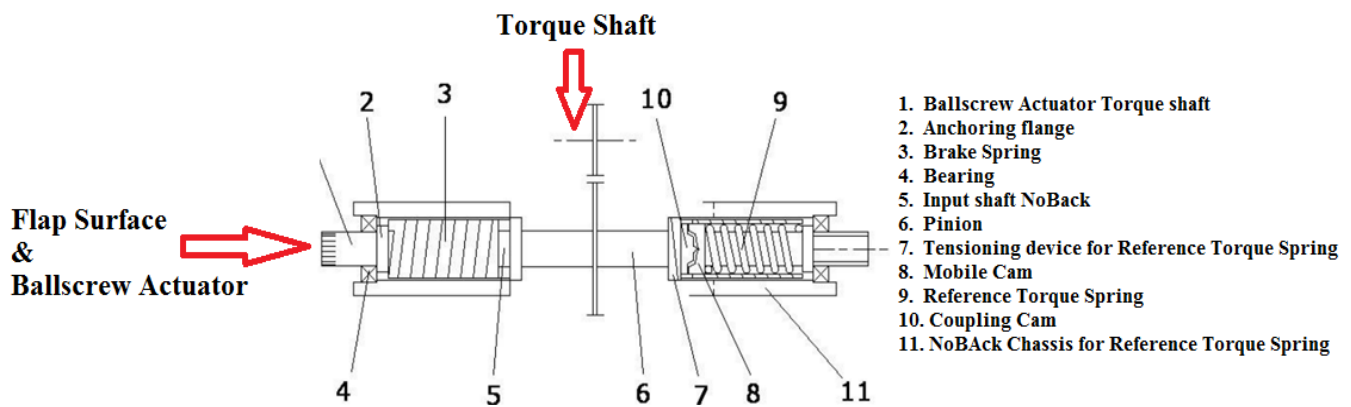


Fig. 4 Schematic Diagram of an irreversibility No-Back Brake (NBB).

As previously mentioned, the flap control systems must satisfy many types of requirements in terms of performance, accuracy, reliability and specified interface with other aircraft systems and primary structure; in particular, the asymmetry limitation between left and right wing flaps represents one of the most critical design requirements as regards actuation, monitoring and position control of these systems.

During normal operating conditions the typical asymmetry between right and left flaps is generally very small: in particular some physical non-linear phenomena as the backlash and the elastic deformation of the mechanical transmission (actuators and torque shaft units) contribute to this asymmetry during the actuation under non symmetrical loads. Referring to the percentage of the full travel of the flap surface, this asymmetry usually produces a value lower than 0.05%, as regards the backlash, and lower than 0.5%, for the elastic deflection. Generally, these narrow angular asymmetries are not able to significantly degrade the maneuverability and controllability of the aircraft, but it must be noted that the secondary flight controls can be affected to many other types of failures able to degrade or compromise its correct functioning: to this purpose, these systems are designed with a conservative safe-life approach which imposes to replace the critical components after a predefined amount of flight hours (or operating cycles)². It must be noted that a mechanical failure can occur in any component of the actuation system (shafts, PDU, actuators). The failure of the PDU or of an actuator results in the inability to operate the affected flap system. Such a failure condition, though being regarded as a major type of failure, is not critical to the flight safety, as it is the case of large asymmetries between the left and right surfaces resulting from uncontrolled shaft failures³.

²The safe-life design approach lacks the possibility to evaluate the possible initial flaws (occurred during manufacturing) that could generate a sudden fault compromising the safety of the aircraft; moreover, such method does not allow to individuate a specific failed component to be replaced instead to intervene to the whole unit (with related inefficiencies and extra costs).

³As example of critical Incident related to large asymmetry flap control system, it is possible to note that on January, 27th 2009 an aircraft model ATR42-320 of the Empire Airline at the airport of Lubbock, Texas, USA had a crash during landing phase.

In fact, if a shaft failure occurs the following events take place: the part of the actuation system upstream of the fracture point keeps rotating with the PDU in the commanded direction until a shutoff command is not given to the PDU, while the portion of the shaft system downstream of the fracture point exhibits a behavior that depends on its design characteristics.

If the actuators are irreversible, this part of the system decelerates rapidly to a stop because the aerodynamic loads acting on the high-lift surfaces cannot backdrive the actuators and the small kinetic energy of the transmission system is soon dissipated by irreversibility losses affecting the system.

Vice versa, if the actuators are reversible, the aerodynamic loads are capable of back driving the failed part of the actuation system, which can accelerate faster when subjected to large loads because of its low inertia.

In this case, in order to stop the uncontrolled surfaces, the actuation system must be either equipped with wingtip brakes (Fig. 1) or with proper irreversibility devices (Fig. 2).

These two configurations are, respectively, based on:

- controlled wingtip brakes (WTB), one for each wing, located at the end of the transmission line, close to the position transducers, that become engaged and stop the system after a failure has been recognized;
- self-acting irreversibility brakes (typically known as No-Back Brakes or NBB) within each actuator, which self-engage when the output of the surface actuator (i.e. the flap actual position) overruns the input shaft⁴ (Fig. 4).

The relative merits of the three solutions (non-reversible actuators, reversible actuators with wingtip brakes, reversible actuators with irreversibility brakes) and which of the three is better is a long debated matter: the maximum asymmetry in failure conditions is greater with the wingtip brake solution, the solution with non-reversible actuators requires higher hydraulic power owing to its lower efficiency and the irreversibility brake solution, that overcomes the shortcomings of the two previous solutions, is more expensive.

⁴This particular system brakes the flap surface, without any electromechanical command, every time that the external load torque results bigger than corresponding reference torque calibrated by the reference torque spring of the NBB system.

Therefore, the most commonly used architecture for high-medium performance aircraft employs the reversible actuators with wingtip brakes and centrally located PDU (of a dual motor type for operational reliability) because it is cheaper and more efficient, nevertheless the associated high asymmetries in case of failure; whereas for low-medium performance aircrafts the most commonly used architecture employ irreversible actuators, nevertheless the associated lower efficiencies.

Whichever design solution is taken, an asymmetry between the surfaces upstream and downstream of the failure develops as long as the PDU is running and the wingtip brakes, if present, are not engaged. This developing asymmetry must be detected and a corrective action taken in order to keep its maximum value within a safe limit by means of appropriate monitoring devices equipped with suitable software whose selection is dealt in [1]. Further, when a failure occurs in the wingtip brakes (reversible actuators architecture), consisting of the inability to apply the proper brake torque to the transmission, a flight safety critical condition can arise, particularly following a previous shaft failure; a similar condition can occur when the irreversible actuators turn to be reversible because of structural vibrations and/or temperature troubles. Another possible trouble can occur when the supply pressure of the hydraulic system drops under a defined value, not allowing position servomechanism proper operations.

The monitoring system must be able to detect and properly correct the above mentioned failures. According to the different failure modes above mentioned, several monitoring techniques are considered. In case of the inability of the wingtip brakes (reversible architecture) to apply braking torques, or in case of irreversible actuators turning to be reversible, the following monitoring technique is employed: if a position error greater than a defined value is produced by a surface position variation without any command variation, then wingtip or irreversibility brake failure is recognized and the hydraulic system is permanently pressurized. In case of a supply pressure drop, the monitoring device is able to shut-off the control system until the correct pressure is restored.

IV. ACTUATION SYSTEM MODELLING

With the aim of develop the aforesaid numerical simulation model, the authors evaluated many physical actuation systems commonly used on-board of modern aircraft in order to define a selected a reference model: the physical model selected as a reference is the Airbus A330 flap actuation system shown in Fig. 5; as previously mentioned, only the flap actuator control system has been considered in the authors' model.

The reference architecture is composed by the following subsystems:

- SFCC: Slats/Flaps Control Computer
- PDU: Power Drive Unit for hydraulic power transformation to mechanical power;
- POB: Pressure Off Brakes stopping PDU shaft to Differential Gearbox in case of major failures;
- SVALVE: Solenoid Valve regulating Power to PDU;
- APPU: Asymmetry Position Pick Off Unit for angular position at the end of kinematic line;
- FPPU: Feedback Position Pickoff Unit for angular position of hydraulic motor shaft;
- IPPU: Indicator Position Pickoff Unit for extraction angle of Flap surfaces;
- WTB: Wing Tip Brakes;
- ECAM: Electronic Centralized Aircraft Monitoring;
- RELIEF-VALVE: shutoff valves to avoid over pressure due to and external loads and activate POB.

The Power Control Unit (PCU) transforms the hydraulic power into mechanical power in order to drive flap surfaces by means of the kinematic line composed by torque shafts, gearbox, and universal joints. Every PCU is fed by two different hydraulic supplies, to give a hot redundancy for aircraft safety and it is generally composed by PDU, SVALVE, POB and Relief Valves.

Given that the above mentioned system is equipped with reversible ballscrew mechanical actuators, in order to overcome the shortcomings reported in the previous section, proper irreversibility devices are needed.

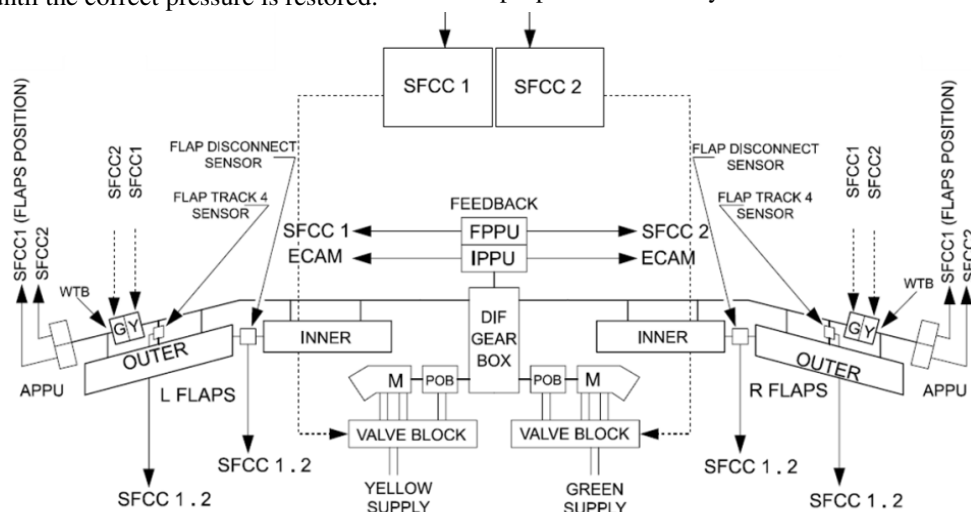


Fig. 5 Schematic of A330 Flap Actuation System

In particular, as shown in Fig. 5, the irreversibility of the whole transmission is performed by means of two wing-tip brakes located at the two outer ends of the shaft system. When a mechanical transmission break occurs (in reversible systems), in order to stop the flap surfaces for each wing (and limit the corresponding asymmetry), the monitoring and control system engages the WTB friction disks, reducing the input pressure of the hydraulic Power Supply, in order to develop a proper braking torque.

Although the WTB is the common used irreversibility system, its asymmetry performances in case of major failure of torque shaft fracture could result unreliable under particular flight conditions (e.g. conditions of very high aerodynamic load), especially using simple asymmetry control based on differential position monitoring [1]. It should be noted that, in case of catastrophic transmission failure, the performance given by the actuation system equipped with WTB could be improved by implementing more effective flap asymmetry monitoring techniques [1-3].

V. PROPOSED NUMERICAL MODEL

As previously described, the primary goal of this work is to propose a numerical simulation model, developed in the Matlab/Simulink® environment, able to simulate a modern flap actuation control system, described in the above paragraphs, improving WTB architecture with innovative monitoring and control algorithm. It must be noted that the characteristics of the proposed simulation model (i.e. modular layout and multi-domain physical-based parametric modelling) allows simulating various flap actuation system configurations taking into account different operating conditions.

Moreover, it allows to test innovative layout solutions and to evaluate the performance and the robustness of new monitoring techniques (using the proposed model as a suitable numerical test-bench in order to support the decision making process during design activities). As previously mentioned, in this work a specific aircraft (i.e. A330) has been considered as reference model for the flap actuation system in order to define the set of physical parameters and boundary condition able to adapt the dynamic responses of the proposed numerical model with the real system ones. In particular, this reference allows to identify (and collect) the different technical data related to:

- Geometries of main components (e.g. Flap surfaces, torque shafts, irreversibility brakes, gearboxes);
- Operative flight conditions (e.g. takeoff, approach and landing phases): using to define aerodynamic loads working on the flap system;
- Operative parameters of main actuation system components (e.g. transmission stiffness, mechanical backlashes, material characteristics, bearings and hinges friction coefficients).

Furthermore, dedicated design algorithm are developed to customize NBB solution for different aircraft configuration as a reference system to evaluate classical WTB solutions improved by innovative monitoring and control techniques.

The numerical model reported in Fig. 6 is consistent with physical model described in the previous paragraph (Fig. 5).

It is composed of nine subsystems:

- 1) Com: an input block that generates surface position commands (Com);
- 2) SFCC: subsystem simulating the Slat/Flaps Control Computer functions (e.g. a PID controller closing the position loop) and the related Monitoring and Asymmetry Control Algorithms; this block generates as output a command signal for control system of servovalve (SV) [2];
- 3) Flapper-Nozzle SV: third order electromechanical model to calculate SV spool displacement as a function of SFCC command signals [4];
- 4) Fluid Dynamic SV Model: fluid dynamic model to correlate spool displacement XS to differential pressure P12 and flow rate QJ managed by SV [5-6];
- 5) PSR: supply pressure generated by electrohydraulic pump;
- 6) PDU: second order numerical model simulating the global power drive units behaviors [3]; it is able to calculate the mechanical power generated by the hydraulic motors taking into account inertia, elastic torque acting on each transmission line, viscous damping, internal friction phenomena and differential pressure supplied by hydraulic systems;
- 7) Transmission Model: motion transmission model evaluating backlash and stiffness of torque shaft and universal joint and gear boxes, detailing specific parameters for left and right line;
- 8) TRL,TRR: Value of aerodynamic loads acting both left and right flap surfaces;
- 9) Left/Right Surface-Actuator: Left/Right Surface-Actuator: second order numerical model that simulates the dynamic response of flap surfaces and ballscrew actuators taking into account static and dynamic friction phenomena and main features of WTB and NBB systems.

Some nonlinear phenomena need to be managed by the numerical simulation model in order to improve accuracy state by means of particular dedicated simulation algorithms. In our proposed simulation model we manage different nonlinear physic phenomena as static and dynamic Coulomb's friction, backlashes, stiffness and viscous dumping and transient hydraulic behavior [7]. For each nonlinear phenomenon a specific numerical approach is defined and integrated within some model subsystems, leaving aside, where is possible, a massive integration related to a more complex numerical effort avoiding a negligible effect on model behaviors. As previously reported, the proposed numerical model has been developed taking into account various researches available in literature; it must be noted that, in terms of numerical modelling, this paper proposes original contributions related to the implementation of the mechanical subsystems (kinematic transmission chain and surface actuators), the development of the different control logics (e.g. multidomain flap asymmetry monitoring implemented by means of Stateflow/Simulink state machines) and the integration of the different contributions/subsystem.

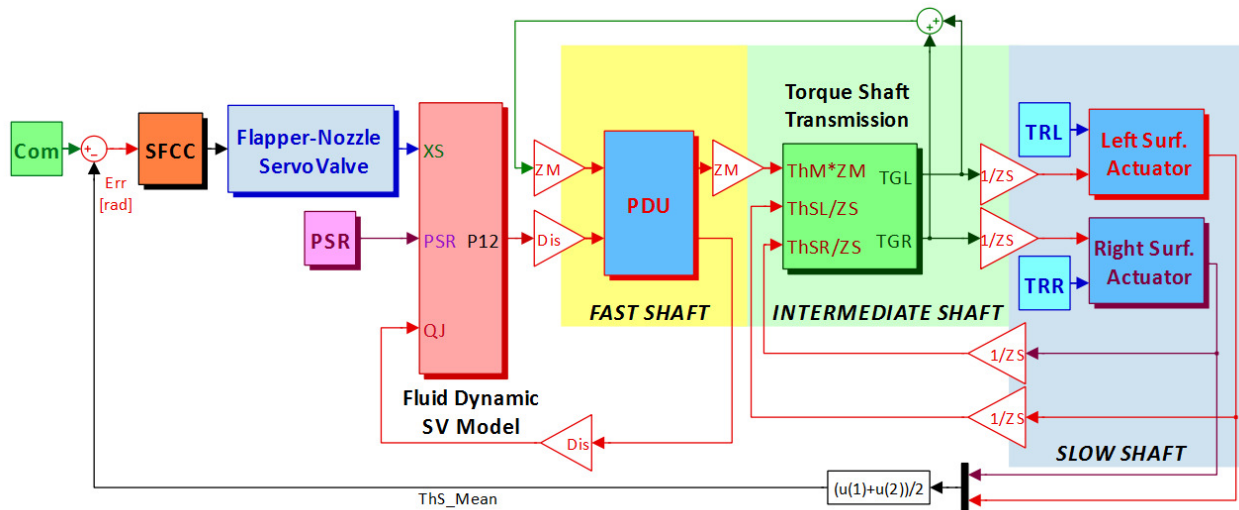


Fig. 6 Proposed MATLAB/SIMULINK® simulation model of flap actuation system

In particular, in the next part of this chapter, will be presented the numerical models developed by the authors to simulate the dynamic behavior of the mechanical items of the flaps transmission line. It must be noted that the mechanical items of the flaps transmission line play an important role in the achievement of the authors' goals because the performances of the whole flap actuation model (sensitivity, accuracy, robustness and computational burden) are significantly influenced by the quality of the modeling of the mechanical parts. The "Torque Shaft Transmission", schematically shown in Fig. 7, simulates the behavior of the whole mechanical transmission: it must be noted that this subsystem is a simplified lumped numerical model simulating the dynamic behavior of the transmission chain (composed by the speed reducer gearboxes and the torque shafts linked together by universal joints). In this numerical model, the whole kinematic line is divided in three subsections representing the high, medium and low speed sections of the physical subsystems: gearmotor model as fast shaft, mechanical transmission model as intermediate shaft and surface-actuators as low shaft. By means of proper conversions, all torque calculations are elaborated within the intermediate shaft so we consider these gear ratios related to speed reducers: Z_M from fast shaft to intermediate shaft, Z_S from the intermediate shaft to low shaft. As Shown in(1) and (2), the mathematical model of the mechanical transmission is calculated as a function of the gearmotor angular position θ_M and the deflection surface angle θ_S (reduced to the same drive shaft); it must be noted that, within the proposed Simulink numerical model, the first angle is indicated as θ_{ThM} , while the second one is referred as θ_{ThSL} for left surface and θ_{ThSR} for right surface. Given that the transmission lines could be affected by mechanical backlashes, the proposed numerical model is able to simulate their effects by means of lumped parameters BLG : as shown in Fig. 7, for each wing the corresponding torque dead bands is calculated in (1) as a function of deformation angle θ_{Trasm} .

$$\theta_{Trasm} = \theta_M \cdot Z_M - \frac{\theta_S}{Z_S} \mp BLG \quad (1)$$

$$\theta_{Trasm} = 0 \text{ IF } -BLG \leq \theta_{Trasm} \leq BLG \quad (2)$$

The torque C_{Trasm} , transmitted by the mechanical shaft is calculated in (3) as sum two terms: an elastic term, proportional to the transmission differential torsion by means of an elastic stiffness coefficient KG (4), and a viscous one, proportional to the differential angular velocity of the transmission by means of a damping coefficient CG (5), representing hysteresis behavior of the material used for transmission components when the aforesaid deformation speed is different than zero.

$$C_{Trasm} = IRG(C_{elast} + C_{visc}) \quad (3)$$

$$C_{elast} = KG \cdot \theta_{Trasm} \quad (4)$$

$$C_{visc} = CG \cdot \dot{\theta}_{Trasm} \quad (5)$$

The parameter IRG is a Boolean value used by the authors to simulate the torque shaft failure (in nominal condition it is set to 1 but, in case of transmission break, assumes null values in order to simulate the annulment of the transmitted reaction torque following the breaking of the kinematic chain).

As shown in (6), the aforesaid stiffness coefficient KG is composed by two different terms considering an arbitrary division of kinematic line useful to introduce the effects of the system within the transmission model.

In particular, the coefficient $KMin$ represents the equivalent stiffness of portion of mechanical transmission between the PDU torque output and the mechanical input of the surface actuator, while the coefficient $KMout$ is related to the equivalent stiffness of the transmission downstream the said actuator input.

$$KG = \left(\frac{1}{KMin} + \frac{1}{KMout} \right)^{-1} \quad (6)$$

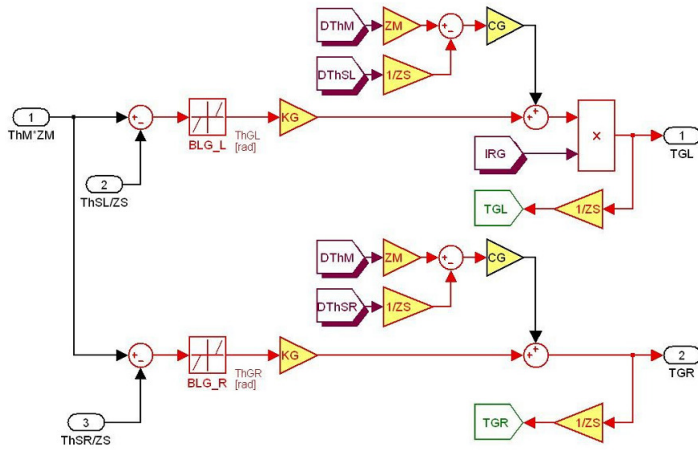


Fig. 7 Block diagram of the mechanical transmission model (left and right transmission lines) equipped with WTBs

By means of an analogous approach it is simulated the CG viscous elastic coefficient as indicated in (7):

$$CG = \left(\frac{1}{CM_{in}} + \frac{1}{CM_{out}} \right)^{-1} \quad (7)$$

Therefore, the mechanical transmission model of the flap actuation system equipped with WTBs has been modelled as shown in Fig. 8. Vice versa, in order to simulate a flap actuation system equipped with NBBs, it is necessary to consider the effects of this irreversibility device on the equivalent values of stiffness and viscous dumping of the transmission system: indeed, the insertion of the no-back brake, because of its elastic compliance, modifies the equivalent stiffness of the kinematic line. As reported in (8), the equivalent stiffness of the mechanical transmission equipped with MBBs are then modelled introducing another term KNB representing the NBB elastic compliance.

$$KG_{NBB} = \left(\frac{1}{KM_{in}} + \frac{1}{KM_{out}} + \frac{1}{RNB} \right)^{-1} \quad (8)$$

$$C_{elast1} = KG_{NBB} \cdot \theta_{Trasm} \quad (9)$$

Furthermore, in this case the elastic torque acting on the flap mechanical transmission is expressed as a function of two different components: the first one, as shown in (9), represents the elastic reaction of the kinematic line (having torsional stiffness KG_{NBB}) under the effects of a given torsional deformation θ_{Trasm} , while the second, expressed in (11), takes into account the internal stiffness of the brake spring KNBF explained in (10).

$$KGF = \left(\frac{1}{KM_{in}} + \frac{1}{KM_{out}} + \frac{1}{KNBF} \right)^{-1} \quad (10)$$

$$C_{elast2} = KGF \cdot \theta_{NBB} \quad (11)$$

Similarly the viscous elastic dumping coefficient CG is modified by the presence of NBB introducing an additional term CNB related to viscous elastic damping between input and output of NBB component.

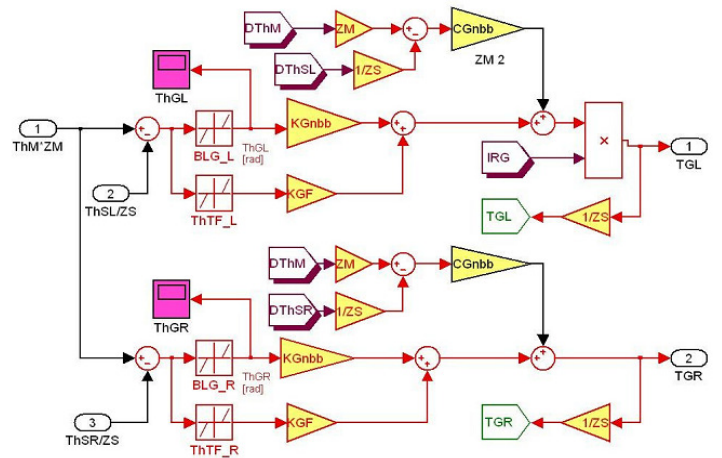


Fig. 8 Block diagram of the mechanical transmission model (left and right transmission lines) equipped with NBBs

$$CG_{NBB} = \left(\frac{1}{CM_{in}} + \frac{1}{CM_{out}} + \frac{1}{CNB} \right)^{-1} \quad (12)$$

$$C_{Visc} = CG_{NBB} \cdot \theta_{Trasm} \quad (13)$$

Another effect due to the introduction of the NBB within flap actuation systems is the internal backlashes of NBB mechanism: it is simulated by means of a coefficient ThTF which represents the amplitude of a dead band linked to C_{elast2} and expressed as a function of the internal springs deformation angle θ_{NBB} ; within this band also C_{elast1} has zero value.

Therefore, as shown in Fig. 8, the numerical model representing the transmission equipped with NBBs takes into account two different backlash type: the first term (called BLG) is shown in (14) and, similarly to the case of systems with WTBs, takes into account the backlashes affecting the mechanical transmission, while the second one (ThTF), reported in (15), evaluates the effects of the eventual NBBs internal backlashes.

$$-BLG \leq \theta_{Trasm} \leq BLG \quad (14)$$

$$-ThTF1 \leq \theta_{Trasm} \leq ThTF1 \quad (15)$$

An important nonlinear physics behavior simulated in this numerical model is related to the Coulomb's friction phenomena. The analysis elaboration for a robust friction model must mathematically describe the physical phenomenon distinguishing between the four possible conditions:

- mechanical element initially stopped which must persist in standstill condition;
- mechanical element initially stopped which must break away;
- mechanical element initially moving which must persist in movement;
- mechanical element initially moving which must stop.

This ability is important, especially in order to point out some specific behaviors concerning the moving parts of whatever mechanical system characterized by dry friction, large displacements and speeds, forward-backward movements and eventual standstill or stick-slip conditions.

According to these considerations, the ability to select the correct friction force sign as a function of the actuation rate sense, to distinguish between the sticking condition (static) and the slipping (dynamic) one, to evaluate the eventual stop of the previously running mechanical element, to keep correctly in a standstill condition the previously still mechanical element or to evaluate the eventual break away of the previously still element itself must be considered as the most relevant merit.

In aeronautical field, such problems are strictly inherent in servomechanism behavior analysis and so it is particularly interesting to employ these numerical methods in the simulation of their dynamics. Many authors have developed models to simulate static and dynamic Coulomb's friction forces as Stribeck, Karnopp, Quinn et al. [8-11].

All these models give simulations not corresponding to the real behavior, manifesting problems of "zero crossing velocity" between static and dynamic friction, or using the values of the main parameters arbitrarily defined by the users which make these models not reliable [12] or, even, make them cause of numerical instability (e.g. the numerical limit cycles, attributable to incorrect identification of the transition between static and dynamic conditions, that characterize the dynamic response of mechanical systems simulated by numerical algorithms that use the SIGN friction model) [13].

In order to avoid the aforesaid numerical problems, the authors have integrated the friction algorithm proposed by Borello et al. [14] (shown in Fig. 9) into the subsystems simulating the dynamic behavior of the different mechanical items. This friction model is based on these variables:

- FSJ: Static Friction Force;
- FDJ: Dynamic Friction Force;
- FF: Resultant Friction Force;
- DThSL: Speed Transmission Line;
- DThSL SP: Reference value (not reset) of DThSL;
- ActTh: Active Force on actuator surface system.

The breaking condition imposed by the model in case of zero crossing of the actuation speed, in case of left wing transmission, is shown in (16):

$$DThSL(t^{n+1}) = 0 \text{ if } DThSL(t^{n+1}) * DThSL SP \leq 0 \quad (16)$$

in which DThSL SP is the reference rotational speed of the transmission subsystems, calculated during the previous integration time and used to perform the aforesaid zero-crossing detection. It must be noted that, if the sticking state imposed by (16) doesn't result a static condition (because the so calculated static friction force is not able to equilibrate the active forces acting on the dynamic system), the comparison between the active and the friction forces acting on the dynamic system would cause its breakaway in the following integration time (incipient motion conditions).

In order to guarantee suitable levels of accuracy and fidelity, the Borello friction algorithm is directly implemented in the numerical models simulating the dynamic response of the mechanical components of the flap actuation system; specifically, it is integrated within the numerical models of PDU hydraulic motors, gearboxes and actuators.

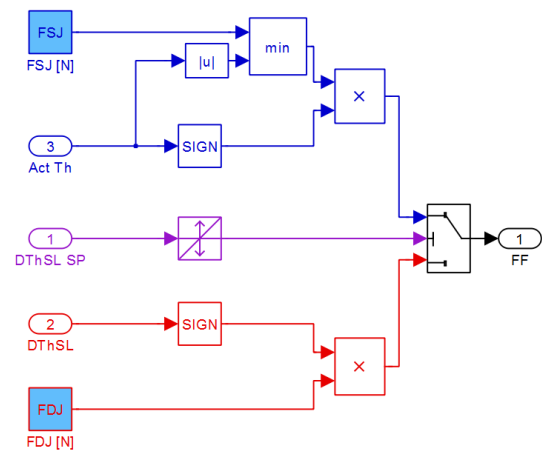


Fig.9: Block Diagram of Reference Friction Model

The actuator surface model considers dynamic equilibrium equation (17) among Act active torques, C_{res} resistant torques, C_{in} inertia component as a function of θ_s angle, $\dot{\theta}_s$ speed, $\ddot{\theta}_s$ acceleration of flap surface.

$$Act - C_{rev} + C_{in} = 0 \quad (17)$$

$$Act = C_{disp} - C_{visc} - C_{Est} \quad (18)$$

$$C_{Res} = C_{Attr} - C_{Irrev} \quad (19)$$

The frictional torques developed by WTBs or NBBs are evaluated by a dedicated algorithm able to take into account their effects and the eventual interactions with the corresponding mechanical systems. Given that several braking systems have been considered, the authors developed different specific simulation models. A design process aimed to define the braking torque developed by the irreversibility brakes provides the operating parameters of the simulation model.

The NBBs are modelled by means of a simplified model implemented in Simulink through a lookup table: the braking torque FF_{nbb} is calculated as a function of the driving net torque ΔTG (for instance, considering the left wing transmission, the aforesaid net torque is calculated as a difference between the driving torque TGL and the corresponding aerodynamic external load TRL). It must be noted that in case of positive values of ΔTG the NBB gives a minimum constant torque value FF_{NBBmin} in every motion condition. Vice versa, when ΔTG takes negative values, the corresponding braking torque evolves according to Fig. 10.

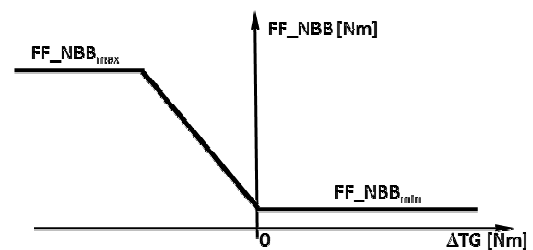


Fig.10 NBB Braking Torque as a function of ΔTG

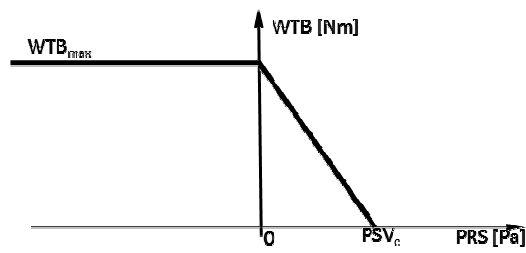


Fig.11 WTB Braking Torque as a function of PSR

The WTBs are similarly simulated by means of a “Simulink Lookup Table” in which the braking torque is calculated (by means of a simplified model) as a function of pressure supply value PSR within the hydraulic circuit driving the WTBs.

The friction discs of the WTBs begin to develop a braking torque when the flap control system commands the braking by closing the dedicated relief valves. When the flap control system activates the WTB, the PSR time transient is simulated by first order model transfer function from nominal value of PSR to PSV_c minimum hydraulic pressure to apply a braking torque, as indicated in Fig. 11.

The Simulink subsystem that implements the proposed integrated reference friction model is shown in Fig.12; it is able to calculate the global braking torque as sum of two components respectively related to the frictional effects on mechanical transmission and NBBs.

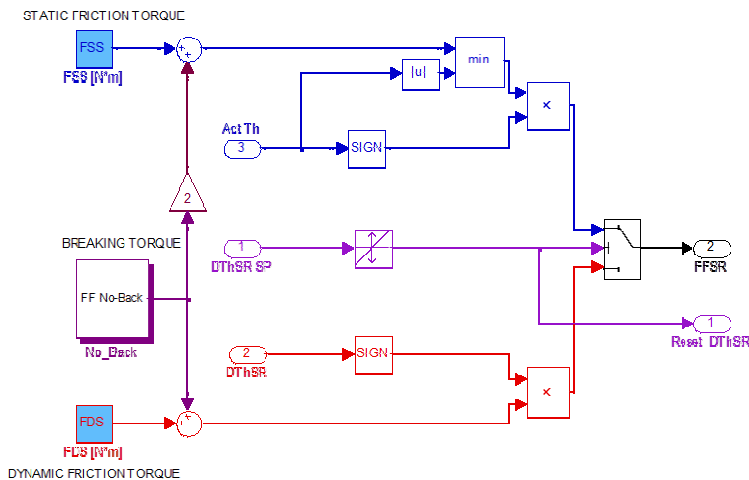


Fig.12: Block diagram representing the NBBs braking torque algorithm integrated into the reference friction model.

VI. AIRCRAFT AND AUTOPILOT MODELLING

In order to assess the amount of perturbations induced on the aircraft attitude by the failures of the flap actuation system, also the lateral-directional dynamics of the aircraft and of its autopilot has been simulated. The dynamics characterizing the aircraft lateral-directional behavior is represented by the usually considered model reported in the current literature [15]. The autopilot control laws have been assumed to be of a PID type, which is adequate to approximate the actual autopilot control within the objective of the present work.

By measuring the aircraft roll angle the autopilot PID controller develops the commands to the ailerons and to the rudder. These flight controls have in turn been simulated as second order systems having speed and position saturations [3]. The aircraft data taken for the simulations are typical of a commercial transport jet aircraft; the purpose of this selection is purely exemplifying, because the aircraft behavior following the failure is substantially similar for all the types of aircrafts.

VII. MONITORING ASYMMETRY TECHNIQUES

The current monitoring technique is based on the detection of the differential position between left and right flap surfaces. Its use generally slightly reduces the asymmetry, but in some cases it may have an unreliable behavior [1]. To overcome these shortcomings different monitoring strategies have been developed by the authors in [2]. The assessment of their effectiveness has been performed using the aforesaid Simulink test bench, evaluating the ability of the different techniques to limit the asymmetry following a torque shaft fracture.

For this purpose, the standard PID controller has been integrated with a numerical algorithm that implements several asymmetry monitoring techniques, characterized by an increasing complexity and performances:

- Differential position control (type 1).
- Differential position and speed control (type 2).
- Differential position and speed conditioned control (type 2a).
- Differential position and speed proportional control (type 2c).
- Differential position and speed variable conditioned control (type 2d).

The differential position control technique, referred as asymmetry monitoring technique *type 1*, performs the flap asymmetry detection by comparing the electrical signals of the position transducers placed at the ends of left and right shaft subsystems. If this difference is greater than a defined limit $\Delta\theta_{Lim}$ persisting for more than a given evaluation time, an asymmetry failure is recognized and shut-off command procedure is activated to engage the WTBs. The improved asymmetry monitoring techniques, which are belonging to the *type 2* monitoring family, are based on detecting both position and speed differences of the two ends of the transmission line [1-3]. If either the position or the speed differential exceeds its established reference threshold for more than a given evaluation time, then an asymmetry is recognized.

VIII. SIMULATION RESULTS

In order to evaluate the performance of the proposed numerical model and its ability to test the aforesaid monitoring techniques, several simulations have been run simulating a mechanical failure of the transmission shaft with a resulting asymmetry between right and left surfaces. It must be pointed out that the asymmetries obtained in case of large loads are always higher than the low load ones [1]; therefore in the present work only loaded actuations are considered.

It must be noted that, in the following figures DthM is the motor speed, ThSL and ThSR are the left and right flaps positions, ThA is the deflection angle of the ailerons and RoA is the aircraft roll angle. Figures 13, 14, 15 and 16 (respectively monitoring techniques 1, 2a, 2c, 2d; failure time as before) show the simulation results for the cases of deploying flaps with reversible actuators under very high opposing loads (it is defined as “very high load condition” the situation in which the actuation system is subject to an aerodynamic load equal to 75% of servomechanism stall load); this load act as opposing to the flap deployment. For all the simulations the transmission shaft failure occurs at time = 0.4 s, while the actuation system is running at the rated speed, following the system start up time. The portion of the flap system downstream the failure decelerates very fast under the action of the very high opposing load and then it accelerates backward until the asymmetry is recognized and the wingtip brake engages providing its braking torque to arrest the system. Meanwhile, the other part of the system is driven by the PDU until the asymmetry monitor provides the shutdown command. It must be noted that in all these figures the asymmetry is given by the differences between the two state variables ThSR and ThSL. Figure 13 puts in evidence that the technique 1 leads to an uncontrollable flight condition, because the aileron efficiency is not sufficient to balance the flap asymmetry. According to the results shown in [2], the maximum flap asymmetry with the resulting roll perturbation and aileron commands progressively decreases moving from monitoring technique 1 to the *type 2* techniques 2a, 2d and 2c (Figg. 14, 15 and 16). It must be noted that the proposed techniques 2c and 2d, in case of very large loads, perform a slightly lower detection time delay in comparison with technique 2a.

IX. CONCLUSIONS

The proposed numerical model, being capable to perform a robust simulation algorithm in order to evaluate within a virtual environment the behavior of a wide range of flap actuation system configurations, can represent an effective support for the decision making process throughout the preliminary design.

As regards the monitoring and control techniques, the proposed simulation model allows to evaluate the effectiveness of each of them into a defined reference architecture.

It is also possible to use this “virtual test-bench” to develop, test and evaluate innovative monitoring and control techniques and conceive/develop new layouts able to improve the performances and the safety of the whole actuation system (e.g. centrifugal or nonlinear viscous brakes, innovative PDU conception or innovative actuators).

ACKNOWLEDGMENT

In conclusion, the authors wish to extend a heartfelt thanks to Professor Lorenzo Borello for his precious support and for his constant assistance during the ideation and development of the concepts that have allowed the realization of this work.

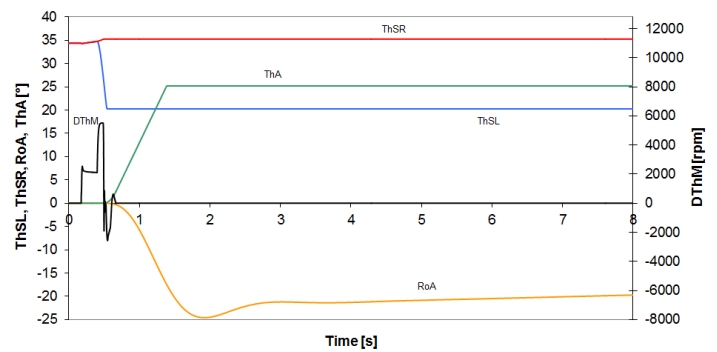


Fig.13 Flaps deployment under very high load – technique 1

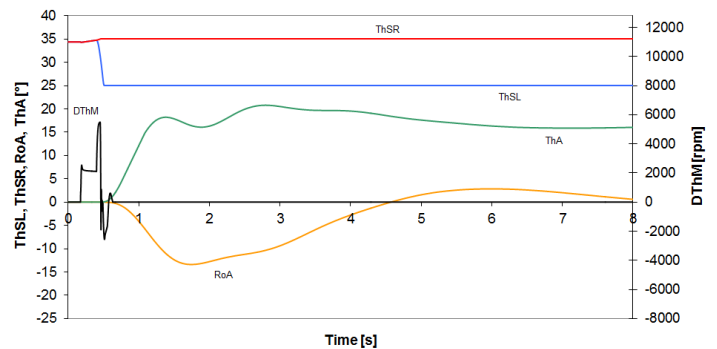


Fig.14 Flaps deployment under very high load – technique 2a

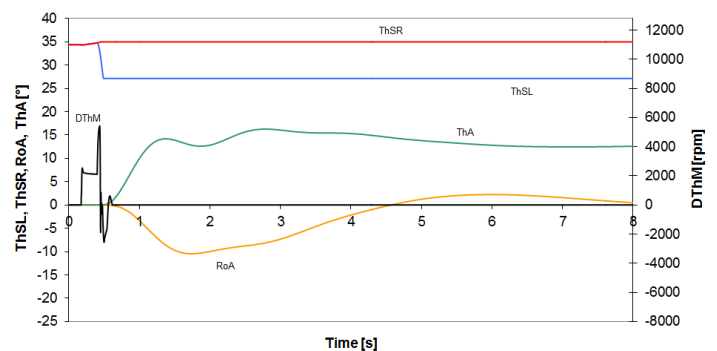


Fig.15 Flaps deployment under high load – technique 2c

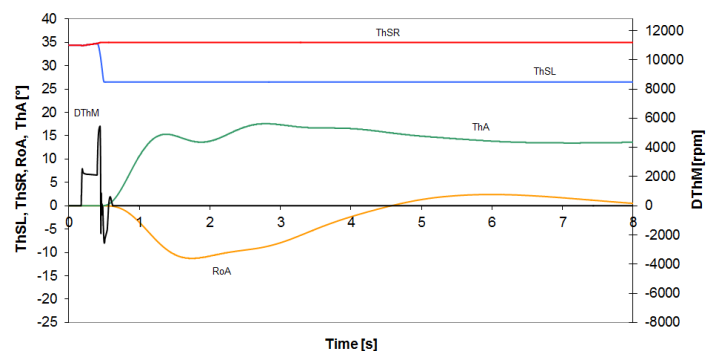


Fig.16 Flaps deployment under high load – technique 2d

REFERENCES

- [1] L. Borello, and G. Villero, "Mechanical failures of flap control systems: proposal of advanced monitoring techniques," *International Journal of Mechanics and Control*, vol. 5, no. 2, 2004.
- [2] L. Borello, G. Villero, and M. D. L. Dalla Vedova, "New asymmetry monitoring technics," *Aerospace Science and Technology*, vol. 13, no. 8, pp. 475–497, 2009.
- [3] L. Borello, and M. D. L. Dalla Vedova, "Flaps Failure and Aircraft Controllability: Developments in Asymmetry Monitoring Techniques," *Journal of Mechanical Science and Technology (JMST)*, vol. 28, no. 11, pp. 4593–4603, November 2014.
- [4] L. Borello, M. D. L. Dalla Vedova, and P. Alimhillaj, "Proposal of Innovative Fluid Dynamic Nonlinear Servovalve Synthetic Models," *International Journal of Mechanics and Control (JoMaC)*, vol. 14, no. 2, pp. 39–49, December 2013.
- [5] F. Fraternali, A. Caimano, P. Maggiore, M. D. L. Dalla Vedova, and L. Pace, "Comparative analysis of a hydraulic servo-valve," *International Journal of Fluid Power*, vol. 14, pp. 53–62, 2013.
- [6] M. D. L. Dalla Vedova, P. Maggiore, and L. Pace. "Proposal of Prognostic Parametric Method Applied to an Electrohydraulic Servomechanism Affected by Multiple Failures," WSEAS Transactions on Environment and Development, pp. 478–490, 2014.
- [7] M. D. L. Dalla Vedova, P. Maggiore, G. Jacazio, and M. Sorli, "A prognostic model for electrohydraulic servovalves," in *Annual Conference of the Prognostics and Health Management Society*, pp. 478–490, 2009.
- [8] D. Karnopp, "Computer simulation of stick-slip friction in mechanical dynamic systems," *Journal of Dynamic Systems, Measurement and Control*, vol. 107, pp. 100–103, March 1985.
- [9] D. D. Quinn, "A new regularization of Coulomb friction," *Trans. Of ASME: Journal of Vibration and Acoustics*, vol. 126, no. 3, pp. 391–397, 2004.
- [10] R. Kikuuwe, N. Takesue, A. Sano, H. Mochiyama, and H. Fujimoto, "Fixed-step friction simulation: from classical coulomb model to modern continuous models," in *International Conference on Intelligent Robots and Systems IEEE/RSJ 2005*, pp. 3910–3917, June 2005.
- [11] D. Guida, F. Nilvetti, and C. M. Pappalardo, "Dry Friction Influence on Inverted Pendulum Control," in *Selected Topics on Applied Mathematics, Circuits, System, and Signals*, Athens, 29–31 December 2009, pp.49–54. ISBN:9789604741472
- [12] L. Borello, and M. D. L. Dalla Vedova, "Load dependent coulomb friction: a mathematical and computational model for dynamic simulation in mechanical and aeronautical fields," *International Journal of Mechanics and Control (JoMaC)*, vol. 7, no. 1, pp. 19–30, 2006.
- [13] D. Guida, F. Nilvetti, and C. M. Pappalardo, "Instability Induced by Dry Friction," *International Journal of Mechanics*, vol. 3, no. 3, pp. 44–51, 2009. ISSN:1998-4448.
- [14] L. Borello, and M. D. L. Dalla Vedova, "A dry friction model and robust computational algorithm for reversible or irreversible motion transmission," *International Journal of Mechanics and Control (JoMaC)*, vol. 13, no. 2, pp. 37–48, December 2012.
- [15] B. Etkin, and D.R. Lloyd, *Dynamics of Flight: Stability and Control*, John Wiley & Sons, 1982.

Dario Belmonte received the M.Sc. at Politecnico di Torino in 2011. Since 2011 he worked as assistant researcher at the Department of Mechanics and Aerospace Engineering and GE Avio Aero srl. His research activity is mainly focused on analysis and numerical simulation of dynamic systems and aerospace servomechanism, integrating correlations between FEM and CAT (experimental data) related to structural vibrational analysis for Gear Box and Propulsor Turbine modules.

Matteo D. L. Dalla Vedova received the M.Sc. and the Ph.D. from the Politecnico di Torino in 2003 and 2007, respectively. He is currently assistant researcher at the Department of Mechanics and Aerospace Engineering. His research activity is mainly focused on the aeronautical systems engineering and, in particular, is dedicated to design, analysis and numerical simulation of on board systems, study of secondary flight control system and conception of related monitoring strategies and developing of prognostic algorithms for aerospace servomechanism.

Paolo Maggiore is a professor at the Mechanical and Aerospace Engineering Department of Politecnico di Torino, that joined in 1992, where he teaches aerospace general systems engineering. Currently his assistant researchers and PhD students are involved in projects ranging from hydrogen fuel cell powered airplanes and UAVs, and health monitoring of flight controls, to multi-disciplinary design optimization of aerospace systems design.